Institution: Loughborough University

Unit of Assessment: B13 Electrical and Electronic Engineering, Metallurgy and Materials

Title of case study: Raising the Standards for Solar Photovoltaics and Accelerating Deployment

1. Summary of the impact (indicative maximum 100 words)

A reduction in planning uncertainties and financial risks of photovoltaics has been achieved by developing internationally accepted standards. Non-standardised characterisation and unreliable energy prediction caused a performance gap between expectations and realistic yields. Loughborough University (Prof. Gottschalg, Dr. Betts) conducted a series of research projects since 1999 which reduced this performance gap. The team consciously transferred developed methods to international standards for energy prediction and device characterisation. Standardisation has, with significant contributions from this team, resulted in the reporting period in a reduction of at least 2% calibration uncertainty, which has a value at today's prices of $1.500,000,000 per year (J. Wohlgemuth [5.1]).

2. Underpinning research (indicative maximum 500 words)

The research at Loughborough University (LU), by Prof Gottschalg (at LU since 1994, academic post from 2000 to date) and Dr. Betts (at LU since 2001, academic from 2010 to date) was undertaken as part of a variety of different funded projects, all addressing the general area of energy yield and characterisation of photovoltaic devices. The overarching question answered in the research is how do photovoltaic devices interact with the environment and how much energy these devices can actually contribute. There are several key influences that were investigated, overall contributing to uncertainty in the energy yield prediction:

- **Device characterisation**. Determining the output at certain (standard) conditions [G3.3, G3.4 and G3.5] developed characterisation methods for energy relevant performance characterisation. The quality of these characterisations is typically proven in intercomparisons between the leading laboratories, which were conducted in G3.4 and organised for G3.1 and G3.2. These brought leading laboratories together and enabled an exchange of ideas which resulted in a proven reduction in measurement uncertainties in the field. It also enabled a modification of the IEC6004-5 standard that was then written up as a standard by Prof. Gottschalg. 3.3 & 3.5 are examples of the resulting work.
- **Technology specific effects.** Different PVg technologies behave differently. G3.5, G3.3, G3.2 and G3.4 considered specific technologies and how these could be measured in a standardised way to reduce uncertainty. 3.2 and 3.3 are examples of the resulting work.
- **Understanding the actual operating environments**. One overarching aim of the work conducted at Loughborough University is to create energy rating standards. This requires the generation of standardised data sets. G3.1, G3.4 and G3.5 worked on this, with a particular link to the European Joint Research Centre's European Solar Test Institute (ESTI) based in Ispra.
- **Modelling the actual site dependent performance.** The strength of the Loughborough team is the modelling of the incident spectrum and the input into the relevant standard sections can be attributed to the submitting team. Work on this was carried out in G3.2, G3.3 and G3.5.

The detailed metrological research has resulted in a number of innovative procedures of how to minimise the uncertainty in measurements or how to assess the uncertainty in 'non-standard' measurements, which were previously assessed by broad assumptions. These measurements are key for an accurate energy prediction as e.g. shown in G3.4 that the metrology of devices is one of the two dominant sources of modelling uncertainty. The detailed assessment methodologies, as e.g. presented in R3.6, enabled the reduction of measurement uncertainty by working on the appropriate components.

It is not always possible to measure the required parameters for any model. The team has developed new measurement apparatuses (G3.3, G3.5) that allow the measurement of device parameters with to date unbeatable repeatability and thus allows a much more accurate assessment of e.g. spectral effects in the laboratory. As an example, the combination of spectral, thermal and intensity changes demonstrated in 3.5, which was the basis of G3.5, has not been achieved since and was the first qualified solar simulator based on LED technology.

3. References to the research (indicative maximum of six references)

Academic Papers Supporting the Impact:
The quality of the journals used for the dissemination is an indicator for the strength of the research, as the journals indicated below are the highest rated journals in the field of photovoltaics.

[3.1] Roy, J., T. Betts and R. Gottschalg (2012). "Accuracy of Energy Yield Prediction of Photovoltaic Modules." Japanese Journal of Applied Physics **51**: 10NF01-11-10NF01-15; DOI: 10.1143/JJAP.51.10NF01

[3.2] Cole, I. R., T. R. Betts and R. Gottschalg (2012). "Solar Profiles and Spectral Modeling for CPV Simulations." IEEE Journal of Photovoltaics 2(1): 62-67, DOI: 10.1109/JPHOTOV.2011.2177445

[3.3] Monokroussos, C., M. Bliss, Y. N. Qiu, C. J. Hibberd, T. R. Betts, A. N. Tiwari and R. Gottschalg (2011). "Effects of Spectrum on the Power Rating of Amorphous Silicon Photovoltaic Devices." Progress in Photovoltaics 19(6): 640-648, DOI: 10.1002/pip.1080

[3.4] Huld, T., R. Gottschalg, H. G. Beyer and M. Topic (2010). "Mapping the performance of PV modules, effects of module type and data averaging." Solar Energy **84**(2): 324-338, DOI: 10.1016/j.solener.2009.12.002

[3.5] Bliss, M., T. R. Betts and R. Gottschalg (2010). "Indoor Measurement of PV Device Characteristics at Varying Irradiance, Temperature and Spectrum for Energy Rating." Measurement Science and Technology 21(11): 1-11, DOI: 10.1088/0957-0233/21/11/115701

[3.6] Strobel, M. B., R. Gottschalg, G. Friesen and H. G. Beyer (2009). "Uncertainty in Photovoltaic Performance Parameters - Dependence on Location and Material." Solar Energy Materials and Solar Cells **93**(6-7): 1124-1128, DOI: 10.1016/j.solmat.2009.02.003

The journals these papers are published in have the most rigorous review process and are amongst the highest cited in the field. Another quality indicator is that the team was invited against significant competition to join an European Metrology Research Project as one of two groups not being National Metrological Institutes (the other being Fraunhofer Institute for Solar Energy – the world's leading PV research institution). The team has also been invited to be the only UK member in the EU-FP7 infrastructure project Solar photovoltaic European research infrastructure (SOPHIA). Further indicators would be that Prof Gottschalg has given invited presentations on the three highest rated conferences in the world (European PVSEC, Asian-Pacific PVSEC, IEEE-PVSC) on the topic. Thus the international community seems to rate the work very highly.

Research Grants which provided the expertise and environment

	Year	**Funder**	**Grant no**	**Title**	**Value [School expenditure]**
G3.1	09-15	EPSRC	EP/H040331/1	Stability and Performance of Photovoltaics (STAPP) PI – Prof Gottschalg	£ 764,799
G3.2	04-06	FU-FP6	SSPI-CT-2003-502411	PV-Catapult Lead Institution – EPIA PI (Loughborough) – Prof Gottschalg	€ 179,620
G3.3	04-09	EPSRC	GR/T03307/01	Advanced Fellowship: Optimised Efficiency of Thin Film Photovoltaic Device (ARF) PI – Prof Gottschalg	£ 472,596

G3.4	06-09	FU-FP6	502775 (SES6)	A Science Base on Photovoltaics Performance for Increased Market Transparency and Customer Confidence (PERFORMANCE) Lead organisation – Fraunhofer Institute ISE PI (Loughborough) – Prof Gottschalg	€ 657,336
G3.5	07-10	EPSRC	EP/D078431/1	Fast Energy Rating for Photovoltaic Devices and Modules (FENRA) PI – Prof Gottschalg	£ 375,110

4. Details of the impact (indicative maximum 750 words)

The research at Loughborough University contributed to an overall significant reduction in the uncertainty in the photovoltaic market by transforming research work into international standards. The impact has been on reduced uncertainties in calibration and energy yield prediction. The impact of calibration or power measurements is largely on the retail value of photovoltaics. Energy impacts on the operation and finance side of the business.

Photovoltaics (PV) is a new energy technology, and one of the key factors slowing down market developments is a perceived risk in the installation of these technologies. There are several different technologies competing for market shares in the field. The devices are rated at standard test conditions and one watt at these conditions would be termed watt-peak, Wp. The overall market size in 2012 is of more than 28 GWp annual installation in 2012, with an installation cost of slightly under 1£/Wp in the majority of markets.

Calibration uncertainty is a risk in the value of the overall market. In today's market (June 2013), one percent uncertainty equates to 750M$/a [5.1]. The team (Prof Gottschalg, Dr. Betts) was instrumental in reducing this as demonstrated e.g. in the EU project Performance where the calibration uncertainty of leading test laboratories was reduced from 5% to less than 2% in standardised power measurements for crystalline silicon and from more than 10% to about 5% for thin film photovoltaics [5.8]. The underlying research which contributed to this was carried out during the Fellowship and the FENRA project and was published amongst other papers in [3.3, 3.5]. The transfer into standards was achieved by contributing to the standard development and the participating bi-annual meetings and appropriate working groups. Prof Gottschalg led the project team for IEC60904-5, which is the most accurate method to extract the cell temperature. Each degree measurement uncertainty in the temperature contributes about 0.5% to the calibration uncertainty, the standard is capable of sub-degree accuracy, while external measurements result in 2-3^{o}C temperature uncertainty. Prof Gottschalg was also on the project team for IEC60904-7, IEC60904-3, IEC60904-9, IEC60904-10 and IEC60891. Each of these standards is a crucial element of the calibration process and has distinct elements linking to work carried out by the team in one of the research projects. It can be assumed that at least 95% of the PV modules produced in the world have been assessed based on the IEC60904 series of characterisation standards and corrected to standard test conditions using IEC60891. Most subsidy schemes require these numbers making the application of these standards mandatory.

Energy yield uncertainty is a risk on the income generated from an installation and thus the financial viability of any investment. The impact claimed here is the better understanding of uncertainties [3.2, 3.6] and better measurements [3.5] and paving the way for standard datasets [3.4]. The impact is difficult to quantify, as production and costs vary for different countries. There are about 100 GWp installed world-wide [5.9], and about 2.5 GWp in the UK. In the UK a system produces around 850 kWh/kWp and the value of a kWh (FIT + self-consumption/ or generation credit) around 0.2£. Thus the impact of one percent uncertainty in production is well in the order of 34M£/a in the UK alone. Uncertainty exists because of a lack of standardised simulations, lack of standardised environmental inputs and lack of validation of existing methodologies on statistical numbers of installations.

The work of the team has been utilised in the published standards IEC61853-1 and the FDIS IEC61853-2. The work on mapping together with Huld et al [3.4] is the foundation of the standard datasets (IEC61853-3). The transfer of research work has been achieved by Prof Gottschalg being part of the project teams and a general recognition of the work by the team. Overall, the work carried out by the team or managed by the team (PV-Performance, PV-Catapult) have resulted in an enhanced understanding of the uncertainties involved and a subsequent reduction of the simulation uncertainty by 2% [5.8].

Key in achieving this impact was participation in the international standards body of Prof Gottschalg. Standards are developed by the International Electrotechnical Commission (IEC) and CENELEC in Europe, with collaborations between the two standard bodies. These normally get mirrored by national standards, which is the responsibility of the British Standards Institution (BSi) in the UK. Prof Gottschalg is active on all these bodies as confirmed by [5.1-5.6].

These standards have been elemental in the market growth. Without these standards enabling the PV deployment, the market would not have grown at the current speed as other technologies have demonstrated with less rigorous standards. In terms of overall market acceleration, the body of work has been essential to further this sustainable technology.

5. Sources to corroborate the impact (indicative maximum of 10 references)
The following sources of corroboration are available at request:

5.1 Chairman of IEC TC82-WG2
The email confirms the participation in the IEC standards body, the contribution to the standards claimed and the value of standards to the market.
5.2 Chairman of CENELEC TC82-WG1
The letter confirms the participation in the EU fora, the contribution to the standards claimed and the value of standards to the market.
5.3 Chairman of BSi GEL82
The email confirms the status as national expert on the relevant topics as well as the impact on the national status.
5.4 Chairman of the German Society for Solar Energy (DGS)
The email confirms the impact of energy rating in the market as well as the standing of the group in the international community.
5.5 International Electrotechnical Commission http://www.iec.ch/
gives official confirmation of Prof Gottschalg's position in the world's standards committee
5.6 CENELEC http://www.cenelec.eu/
gives official confirmation of Prof Gottschalg's position in the European standards committee
5.7 BSi http://www.bsigroup.co.uk/en-GB/
gives official confirmation of Prof Gottschalg's participation in the standards development of the BSi
5.8 FP6 project Performance final report
demonstrates the achieved uncertainty improvements by the team as well as others which have been achieved as part of the project and in comparison to the PV-Catapult project. This verifies the claims of the improvements in calibration uncertainty of the leading EU laboratories and the status of the CREST team having a good standing amongst them.
5.9 IEA-PVPS, various reports on the status of the industry (http://www.iea-pvps.org/) confirms the various statements on the PV market size and the corresponding attempts to quantify impact figures.